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Computer simulation of a downdraft wood gasifier for tea drying

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Abstract

A gasifier has been fabricated in Sri Lanka for the tea industry, but there is a lack of knowledge of the effect of certain key operating parameters and design features on its performance. Experimental testing of the design under various conditions has produced data that has then been used to calibrate a computer program, developed to investigate the impact of those parameters and features on conversion efficiency. The program consists of two sub-models of the pyrolysis and gasification zones, respectively. The pyrolysis sub-model has been used to determine the maximum temperature and the composition of the gas entering the gasification zone. The gasification zone sub-model has been calibrated using data gathered from the experiments. It was found that a wood chip size of 3–5 cm with a moisture content below 15% (d.b.) should be used in this gasifier. Feed material with a fixed carbon content of higher than 30% and heat losses of more than 15% should be avoided. For the above parameters, the gasification zone should be 33 cm long to achieve an acceptable conversion efficiency.

Keywords: Downdraft gasifier; Tea drying; Simulation; Conversion efficiency

1. Introduction

A previous feasibility study conducted by Jayah et al. [1] indicates that wood gasifiers appear to be a viable option to produce the hot air for drying tea in Sri Lanka. A subsequent study [2] compared the performance of a locally produced downdraft gasifier with an imported unit and found that the units had a similar conversion efficiency. [1] The study also showed that the life cycle cost of energy from the gasifier would be 8% lower than the cost of energy from the current wood fired air heating system. At the same time, savings in wood consumption of 12% could be expected. Furthermore, the study concluded that adequate expertise and support for the use of gasifier technology

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[1] In this paper, the conversion efficiency is based only on the heating value or chemical content of the cooled output gas and does not include the sensible heat the hot gas contains when produced. Hence the conversion efficiency figures reported in this paper are approximately 30% lower than those reported in [2].

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by the tea industry was also available in Sri Lanka because of its success in their crematoria industry.

However, there is still a lack of knowledge of the optimum range of operating parameters and the influence of some design features of the locally produced downdraft gasifier on conversion efficiency. This paper therefore describes the selection and development of a model used to study the downdraft gasifier designed by the National Engineering Research and Development (NERD) Centre in Sri Lanka. Data from a series of experiments was used to calibrate this model, which has then been used to investigate the effect of chip size, moisture content, inlet air temperature, heat loss and throat angle on conversion efficiency. Based on these simulations, the optimum range of these operating and design parameters, and the optimum gasification zone length for the NERD downdraft gasifier are selected.

2. Model selection

Jayah et al. [3] conducted a survey to identify the possible models that could be used to investigate the performance of the NERD downdraft gasifier. It was found that the model developed by Chen [4] could be used, but with some modifications. The objectives of Chen's model were to estimate the length of the gasification zone, reactor diameter and to investigate the dependence of reactor performance on operating parameters such as the feedstock moisture content, chip size, reactor insulation, input air temperature and gasifier load. Chen's model consists of three parts. The first part determines the amount of oxygen needed for a fixed input of fuel at a specific operating condition. The fuel-to-air ratio estimated from this first part is then used as an input to the second part of the model, where the drying, pyrolysis and combustion zones are all lumped together and considered as a single zone. The outputs from this "lumped" zone are the product concentrations and the temperatures of the gaseous and solid phases leaving the zone. These calculated concentrations and temperatures are then used as inputs to the third part of the model. Here the temperature profile along the axis of the gasification zone, gas composition, conversion efficiency and the length of the gasification zone at any given time interval are predicted.

The main weakness of Chen's model is the over-prediction of the gas exit temperature from the "lumped" zone due to an unrealistically low estimate of heat loss and the omission of CO and H_2 in the pyrolysis gas. Therefore modifications were required to overcome these deficiencies and also to suit a reactor with a variable rather than a constant gasification zone diameter.

3. Model development

In order to overcome the over-prediction of the pyrolysis zone exit temperature, the flaming pyrolysis model developed by Milligan [5] has been used in place of the algorithms used by Chen. The aim of Milligan's flaming pyrolysis zone model is to calculate the composition of the product gas entering the gasification zone in terms of CO, H_2, CO_2, H_2O, CH_4 and N_2. It has been found that the predictions of Milligan's flaming pyrolysis model are more realistic than those made using Chen's "lumped" zone concept [5]. The constant reactor diameter, assumed in the final section of Chen's model, was modified with a variable diameter to suit the throat configuration of the NERD gasifier. As a result, the model used in this study consists of two sub-models, namely of the flaming pyrolysis and gasification zones.

The flaming pyrolysis zone sub-model is used to determine the maximum temperature and the product concentration of gas leaving that zone. The concepts of equilibrium in chemical reactions with mass and energy balance principles are used in the model development. The calculated concentrations and temperatures predicted by the flaming pyrolysis zone sub-model are then used as inputs to the gasification zone sub-model. The gasification zone sub-model assumes that a single char particle moves vertically downwards along the vertical axis of the gasifier. This sub-model includes a description of the physical and chemical processes, flow equations, transport phenomena and conservation principles. A Fortran computer program has been written [6] to calculate the characteristic profiles of temperature, gas concentration and conversion efficiency along the reactor axis. While the focus of this project was to investigate the effect of various parameters on efficiency, the model

could be used to determine the variation of $CO:H_2$ ratio with fuel moisture content, but only at a fixed pressure.

4. The experimental system

The experimental test rig used to collect data to calibrate the gasification zone sub-model consisted of the gasifier, blower, airflow meter, data logger, computer, orifice plate, manometer, cooling system, gas sample collector and thermocouples. Figs. 1 and 2 show the experimental system both schematically and pictorially, while Fig. 3 gives the main dimensions of the gasifier.

The 80 kW_{th} test gasifier has an inner reactor diameter of 0.92 m and is 1.15 m long. The inner and outer walls of the drum are made from 22 gauge mild steel and 1.4 mm thick galvanized iron respectively and there is a small air gap between the walls. Air is supplied to the combustion zone through 12 air nozzles, 6-mm in diameter, located 100-mm above the throat. The 100-mm diameter throat is lined with high alumina castable and is surrounded by firebricks to withstand the high temperatures in the combustion zone. No insulating materials have been used in this gasifier design. The 220-mm long gasification zone diverges at angle of 61° from the horizontal. Below this zone there is a grate to catch any unreacted char and an ash chamber lies below the grate. A 50-mm diameter galvanized steel pipe delivers the gas from the system to the load.

5. Experimental procedure

The main fuel wood used in the tea industry in Sri Lanka is rubber wood. It accounts for 70% of the total fuel wood consumption by the industry [7] and thus rubber wood has been selected as the feed material for this study. Accordingly, rubber wood logs with initial moisture content of 54–100% (d.b.) were initially sun-dried for three weeks. The partially dried wood was then cut into variously sized chips (3.3–5.5 cm) and then sun-dried again for another week until the desired moisture level of 11–18% (d.b.) was reached. The moisture content of rubber wood was determined by the percent weight loss of a 10 g sample at 105°C constant temperature for 1 h. Three samples were tested for each run and the average value was taken.

The process of gasification is governed by the characteristics of the feed materials used and so an understanding of the properties of feed materials is necessary in order to evaluate their utility as feed stocks for the gasification process [4]. The higher

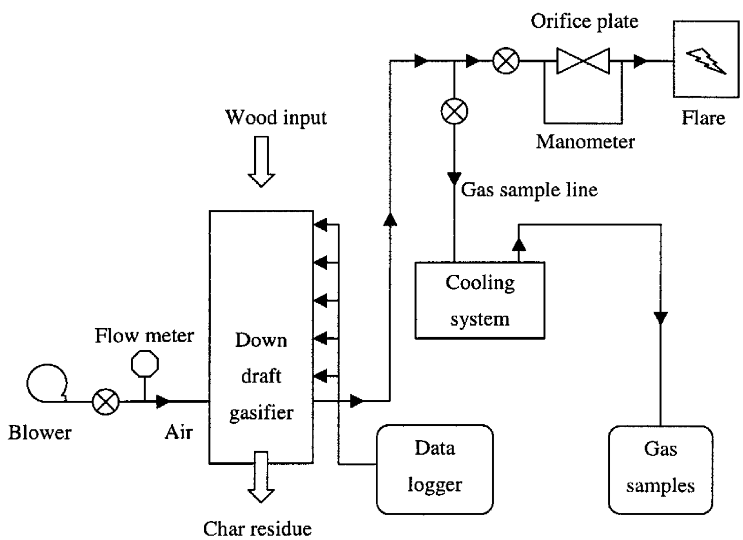

Fig. 1. Schematic diagram of the experimental system.

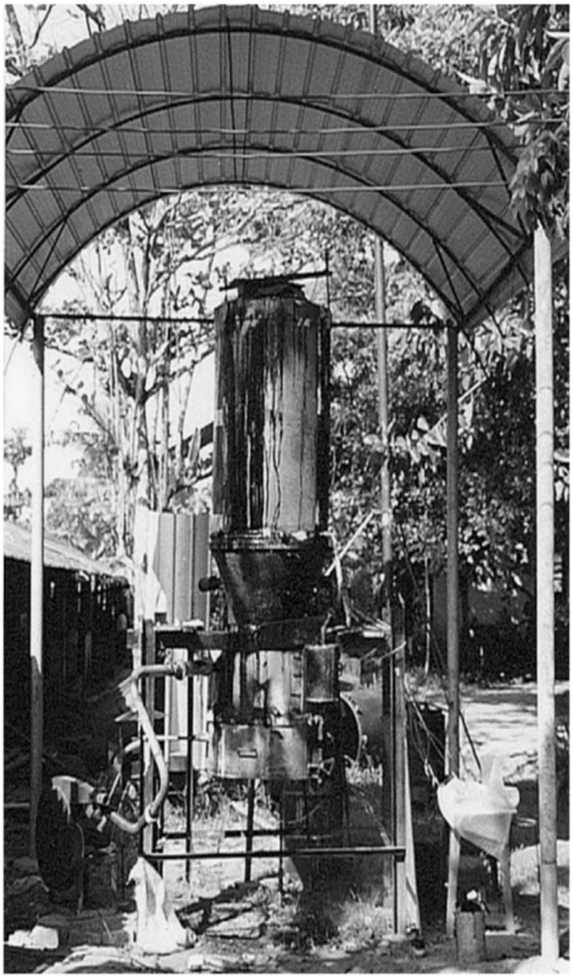

Fig. 2. The test gasifier.

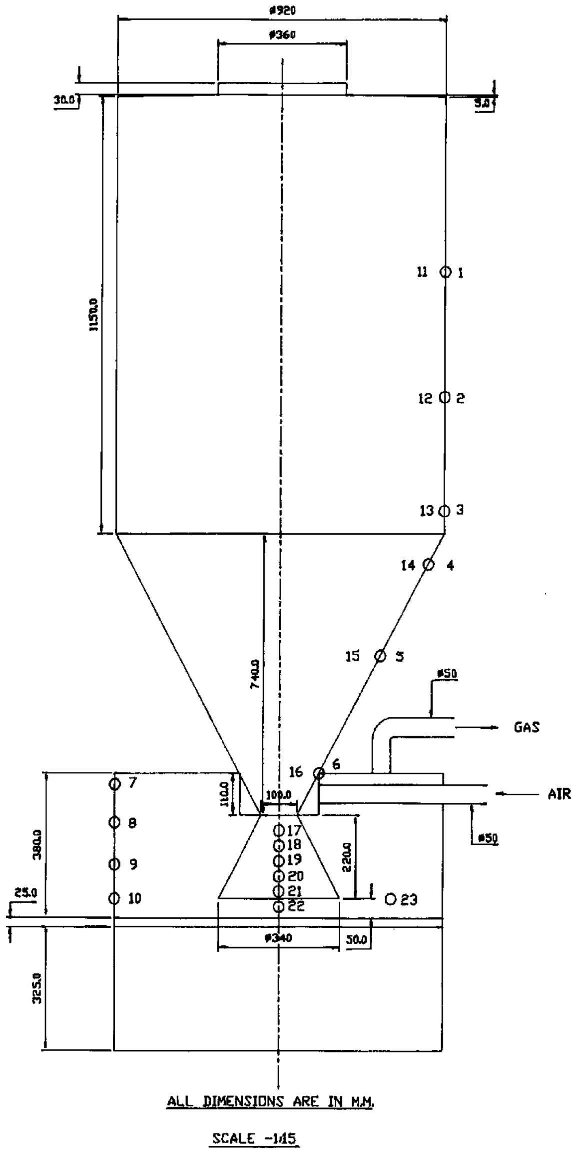

Fig. 3. Schematic diagram of the test gasifier.

heating value, proximate and ultimate analyses of the rubber wood were therefore all determined. This work was carried out by a commercial company.

Prior to each operation of the gasifier, the weight of wood chips to be used was recorded. The blower was then switched on and the airflow was adjusted to the desired level. The chips were ignited through a port in the throat of the gasifier. Once gas production began, measurements of the key variables were made. Airflow was measured on the exit side of the blower by the flow meter and pressure measurements were made either side of the orifice plate using the manometer (Fig. 1). Axial temperatures in the gasification zone and the outer surface of the gasifier were measured using K- and T-type thermocouples. Ambient conditions were measured using a dry bulb-wet bulb thermometer and the outlet gas temperature was measured using a digital thermometer.

To ensure that there was no “bridging” i.e. fuel lodging in the throat and possibly leading to a shortage of char in the gasification zone, the gasifier was “shaken” once during the experimental and trial runs.

The gas burned steadily with a blue-red colour flame, and was considered to indicate reliable operation. A sample of product gas was collected during each operation of the gasifier. A commercial company using gas liquid chromatography analyzed the samples. A molecular sieve column was used to analyze H_2, O_2, N_2, CO and CH_4while a Carboxine 1000 column with temperature program 50–225°C at 20°C min^{-1} was used to determine CO_2.

The experiments were conducted for three chip sizes and for four air–fuel ratios.

6. Experimental results

The proximate and ultimate analyses of rubber wood used in the experiments are given in Tables 1 and 2. The proximate analysis agrees well with the data reported by Hoi et al. [8]. The measured higher heating value of the rubber wood used was 19.6 MJ kg^{-1}, which is 6% higher than the figure reported by the same authors. The bulk density of rubber wood, calculated by dividing the weight of air dried chip samples by the volume occupied, was found to be 314–330 kg m^{-3}. The range of moisture content of the samples varied between 12.5% and 18.5% (d.b.). Gas composition data is available for nine of the experimental runs of the gasifier and varies with moisture content, chip size and air–fuel ratio.Table 3 shows the results of the analysis of the gas sampled during these runs. A mass balance on the gasifier was also carried out (Table 4). In this analysis, tar and water vapour in the product gas and ash production were not measured directly and are included in "unaccounted material", which represent 7–9% of the output material. Fig. 4 shows typical temperatures in the gasifier, measured by a selection of the thermocouples (Fig. 3) during one trial. The temperature profile clearly shows that in a gasifier the area of interest, in terms of conversion efficiency and heat loss, is in the last 40 cm of the unit.

Table 1
Proximate analysis of rubber wood

Parameter	Proximate analysis (% d.b.)
Volatile matter	80.1
Fixed carbon	19.2
Ash content	0.7

Table 2
Ultimate analysis of rubber wood

Parameter	Ultimate analysis (%)
C	50.6
H	6.5
N	0.2
Ash content	0.7
$O = \{100 - (C + H + N + Ash)\}$	42.0

7. Model calibration and use

The purpose of the modeling is to be able to study the effects of various operating and design parameters on the conversion efficiency of the NERD gasifier. In order to carry out this parametric study, it was first necessary to calibrate the model using the gas compositions measured in the experiments. In calibrating the sub-model, the amount of methane predicted was adjusted in such a way that it was equal to the amount of methane measured experimentally in the product gas. A typical comparison between the model predictions and measurements using the 2.5 cm chips (Run No 7) is shown in Table 5. It can be seen that the gas compositions predicted by the gasification zone sub-model are within ±5.8% of the measured values. A typical comparison between the measured and predicted temperatures in the gasification zone is shown in Fig. 5. While there was a tendency to under-predict and over-predict the temperatures generated in the central and end portions of the gasification zone, respectively, the expected trend is nevertheless evident with sufficient accuracy. The predictions of the gasification zone sub-model were therefore considered to be satisfactory to study the performance of the NERD gasifier and a set of computer simulations have been carried out to investigate the effects of various operating parameters on conversion efficiency. The parameters and range of values used in these simulations is shown in Table 6.

Table 3
Summary of gas analyses from nine experimental runs of test gasifier

Run no.	Chip size (cm)	M/C (%) (d.b.)	Air/fuel ratio	CO (%)	H_2 (%)	CO_2 (%)	CH_4 (%)	N_2 (%)	Gas flow rate ($m^3\,h^{-1}$)
1	3.3	18.5	2.03	19.6	17.2	9.9	1.4	51.9	52.4
2	3.3	16.0	2.20	20.2	18.3	9.7	1.1	50.7	57.7
3	3.3	14.7	2.37	19.4	17.2	9.7	1.1	52.6	59.7
4	4.4	16.0	1.96	18.4	17.0	10.6	1.3	52.7	53.6
5	4.4	15.2	2.12	19.7	13.2	10.8	1.3	55.0	62.1
6	4.4	14.0	2.29	18.9	12.5	8.5	1.2	59.1	62.5
7	5.5	14.7	1.86	19.1	15.5	11.4	1.1	52.9	51.9
8	5.5	13.8	2.04	22.1	12.7	10.5	1.3	53.4	62.5
9	5.5	12.5	2.36	19.1	13.0	10.7	1.2	56.0	63.5

Table 4
Material balance of the gasifier

Material input (kg/h)					Material output ($kg\,h^{-1}$)				
Air	Feed	Wood moisture	Air moisture	Ash	Gas	Water	Char	Ash	Unaccounted material
55.6	18.6	3.4	1.0	0.1	71.0	1.4	0.7	0.1	5.5
55.6	20.9	2.6	1.0	0.1	69.9	1.2	2.1	0.1	6.9

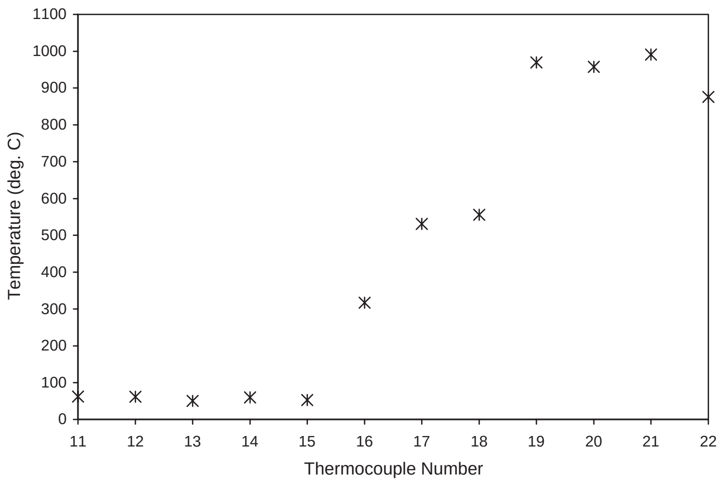

Fig. 4. Typical temperature profile through gasifier during operation.

Table 5
Comparison of predicted and measured gas composition for 2.5-cm chips

Dry gas composition (% by vol.)	Predicted	Measured
CO	18.3	19.1
H_2	16.4	15.5
CO_2	11.1	11.4
N_2	53.2	52.9
CH_4	1.1[a]	1.1

[a]Assumed.

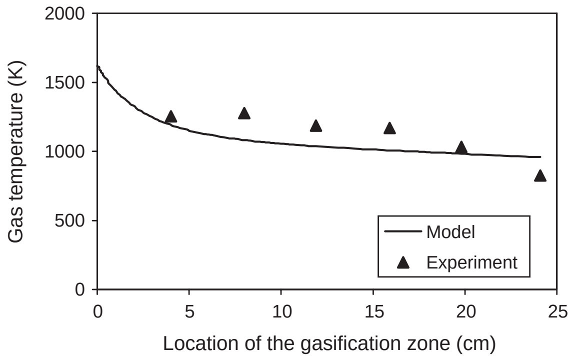

Fig. 5. Comparison of measured and predicted temperatures along axis of gasification zone for air–fuel ratio of 2.20.

Table 6
Range of parameters used for simulation study

Parameter	Range
Wood moisture content (% d.b.)	0–30
Heat loss (% input energy)	5–15
Chip size (cm)	1–5
Air temperature (K)	300–600
Throat angle (°)	30–90

8. Simulation results and discussion

Three of the parameters studied (air inlet temperature, chip size and moisture content) are operating parameters over which the user has control and the remaining two parameters (heat loss and throat angle) are functions of the gasifier design. The variation in conversion efficiency along the gasification zone for each of these parameters was investigated and the simulation results are presented and discussed below. For various values of four of these parameters, the optimum length of gasification zone and the efficiency at that length is then summarised and compared with the efficiency levels achievable with the current NERD design.

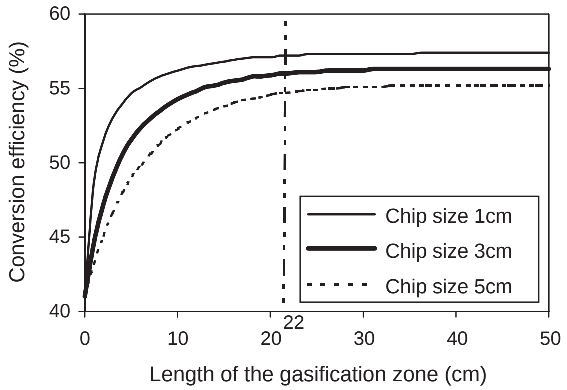

Fig. 6. Variation of conversion efficiency for different chip sizes.

8.1. Chip size

The size of fuel wood chip is an important parameter which affects the char conversion rate and hence the conversion efficiency. The size of the chips used mainly depends on the diameter of the gasifier. Milligan [5] used 0.6 cm chips in a laboratory-scale gasifier with a reactor diameter of 7.5 cm. In contrast, Walawender et al. [9] used chips as large as 4.7 cm for a commercial scale gasifier with a reactor diameter of 60 cm.

The variation of conversion efficiency along the gasification zone for different chip sizes is shown in Fig. 6. It can be seen that as the chip size increases the length of the gasification zone must also increase before the conversion reaches its maximum. Thus larger particles need longer reactor lengths to achieve the maximum conversion. Char conversion consists of two processes namely, fast conversion and slow conversion. Fast conversion of char takes place at the entrance of the gasification zone due to the fast reaction rate [4]. Smaller particles are more likely to get converted to gases completely before the slow conversion begins because of their size and fewer

diffusional limitations during the reaction process [4]. Thus gasifiers with shorter reactor lengths need small chips. With the same environmental conditions, larger chips also undergo the same fast conversion but because of their size, complete conversion may not be possible. Larger chips undergo the remaining slow conversion and thus need a longer reactor length prior to leaving the gasification zone. As a result of faster char conversion, smaller chips increase the conversion efficiency compared to larger chips. Sizes of chips used in the NERD gasifier varied from 1 to 5 cm. But in general, 5 cm chips are preferred due to their lower preparation cost, which is significant for commercial gasifiers. The gasification zone length of the NERD is 22 cm. It can be seen from Fig. 6 that for a gasification zone length of 22 cm, the conversion efficiency is almost 55% for chip size of 5 cm. If this size is reduced to 3 cm, the conversion efficiency increases by 1%. The optimum gasification zone length is defined as the length at which the efficiency is 99.5% of the ultimate conversion efficiency. For a 5 cm chip size, the optimum length of the gasification zone is approximately 33 cm.

8.2. Moisture content

The moisture content of the feed material is one of the main characteristics, which affects the composition of the product gas [10]. The effects of moisture on the recoverable heat are very significant due to the heat requirement for vapourizing the moisture and superheating the vapour [11]. Generally for gasifier operations, fuel wood with a low moisture content is preferred because of its higher gross energy content. Reed and Das [12] have reported that moisture contents higher than 67% (d.b.) make the product gas too lean for ignition. Although lower moisture contents are preferred to produce a high-quality gas, they further stated that it is desirable to maintain a level at least below 33% (d.b.) to produce a combustible gas.

Fig. 7 shows the variation of conversion efficiency along the gasification axis for various moisture contents. Although it is not practically possible to achieve a 0% moisture content, this figure has been included to show the maximum possible efficiency. It can be seen that the conversion efficiency decreases with increasing moisture contents. This is due to the fact that a higher amount of energy is consumed in evaporating

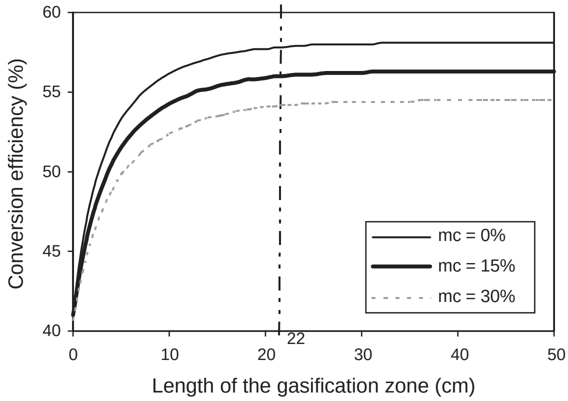

Fig. 7. Variation of conversion efficiency for different moisture contents.

the moisture in the wood, which subsequently reduces the temperature of the gas. The lower temperature reduces the reaction rate and thereby the conversion efficiency. The moisture content of the wood chips used in NERD gasifier varied from 12.5 to 18.5 (d.b.). It can be seen from Fig. 7 that for average moisture content of 15% (d.b.), the conversion efficiency of the NERD gasifier is 56% at 22 cm along the gasification zone whereas the optimum length occurs at approximately 32 cm.

8.3. Inlet air temperature

Generally ambient air at 300 K is used for gasification. However, Chen [4] stated that a higher inlet air temperature improves the conversion efficiency. Conversion efficiency increases as the inlet air temperature increases because hot air provides additional enthalpy necessary for reaction, thereby decreasing the air fuel ratio. The effect of preheating the input air temperatures to 450 and 600 K has therefore been investigated. Fig. 8 shows that higher inlet air temperatures are beneficial to gasifier performance, but the effect is only marginal. The conversion efficiency increases from 56.0% to 56.5% when the inlet temperature increases from 300 to 450 K. For an air input of 50 kg h^{-1}, which a typical figure for the NERD gasifier, approximately 2 kW of energy would be required to raise the temperature of air from 300 to 450 K. This is approximately 3% of the 70 kW$_{th}$ gasifier capacity. However, in tea drying, the temperature of the exhaust

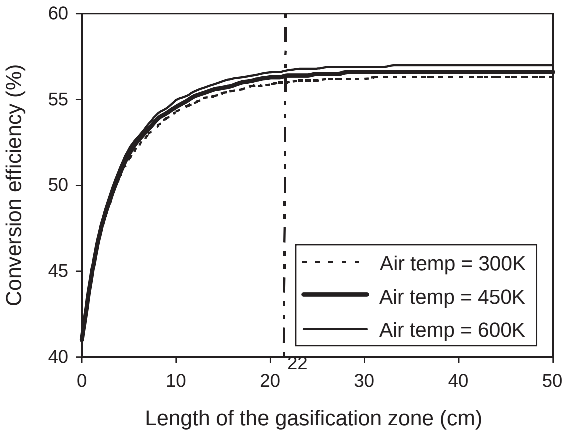

Fig. 8. Variation of conversion efficiency for different air temperatures.

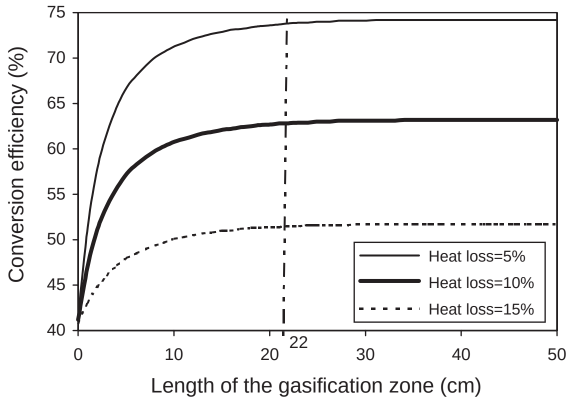

Fig. 9. Variation of conversion efficiency for different heat losses.

gas is around 150°C [13] and this could be used in combination with a heat exchanger to raise the temperature of inlet air. However, due to the additional expense involved, it is unlikely that achieving only a small increase in conversion efficiency in this way is economically viable.

8.4. Heat loss

According to Chern [14], a heat loss of 10% is acceptable for a commercial gasifier. The results of an energy balance conducted on the NERD gasifier found the heat loss was approximately 12.8% [6], the lack of insulation on the gasifier body being a major contributor to this loss. Unaccounted losses in the balance represented about 5% of the energy output. This included losses due to tar production, which could not be accurately measured. The variation of conversion efficiency for varying degrees of heat losses is shown in Fig. 9. It can be seen that of all the parameters investigated, the heat loss has the greatest effect on the conversion efficiency, which decreases by approximately 11% for every 5% increase in heat loss. This is because the high heat loss lowers the reactor temperature, which in return reduces the gasification reaction rates and the conversion efficiency. This is more significant for smaller reactors because in terms of fluxes (based on reactor cross-section area) the heat loss is high for gasifiers with smaller reactor diameters as the surface-to-volume ratio will be higher. Fig. 9 indicates that a 12.8% heat loss (i.e. the NERD gasifier) will result in a conversion efficiency of approximately 56% at a gasification zone length of 22 cm, although the optimum gasification zone length is approximately 26 cm. Although the decrease in conversion efficiency is considerable for any increase in heat loss, the cost associated in reducing the heat loss e.g. increasing gasifier insulation must be considered to ensure economic benefit.

8.5. Throat angle

Throat angle is a special unique feature of downdraft gasifiers and the effect of this on conversion efficiency is important. In selecting the range of the throat angles, the values of 30°, 60° and 90° were selected to include the existing angle of 61°. Fig. 10 shows the variation of conversion efficiency along the gasification zone axis for different throat angles. The conversion efficiency decreases as the throat angle increases, because the divergent effect of the throat decreases the temperature and hence the reaction rate. However, the smaller angles also need a longer gasification zone length to reach their optimum efficiency. The effect of throat angles is not significant until the conversion process reaches the gasification zone length of 10 cm. For a throat angle of 61° i.e. the NERD gasifier, the conversion efficiency is 56% at the gasification zone length of 22 cm.

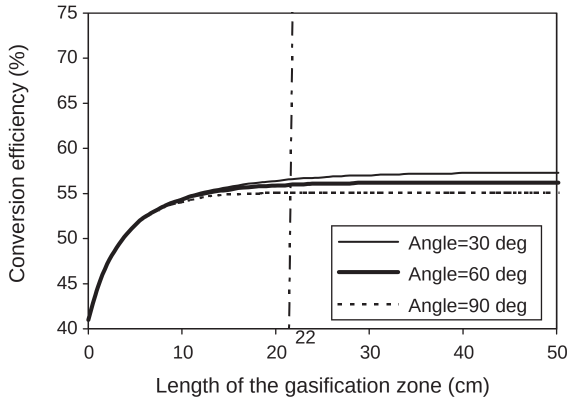

Fig. 10. Variation of conversion efficiency for different throat angles.

8.6. *Optimum gasification zone length*

Table 7 compares four of the above operating and design parameters with the efficiency achievable at 22 cm and at the optimum gasification zone length. In this comparison, the effect of increasing the inlet air temperature is not included because the efficiency gains achievable are considered to be too small. It can be seen that 1 cm chips tend to increase the maximum efficiency by only 1% compared to 3 cm chips, although the gasification zone length may be reduced by 25%. However, these benefits would only be achieved with a higher fuel wood preparation cost. Although it would be advantageous to use rubber wood with a moisture content below 10% (d.b.), in reality it would be difficult to dry the large quantities of chips needed for a commercial type gasifier to this level. If wood chips are given sufficient sun exposure, the moisture content can be reduced to 15%, which gives a conversion efficiency of 56%.

As noted earlier, a decrease in heat loss has the greatest effect in terms of improving efficiency. However, the optimum gasification zone length needs to be increased at the same time as reducing the heat loss. However, the resulting gains in efficiency are likely to far outweigh the increased cost of increased insulation and reactor length. An increase in the existing throat angle would have some beneficial effect in terms of efficiency, but as already noted the length of the gasification zone would have to be increased. Therefore the relative costs of this exercise would have to be carefully evaluated against the potential gains.

9. Conclusions

Of the five parameters investigated in this section, the moisture content of fuel wood and heat loss are the main variables affecting downdraft gasifiers. Moisture content and heat loss have greater effects on reactor temperature and hence on the conversion efficiency. Reducing the heat loss from the gasifier is very beneficial in terms of conversion efficiency and this can be achieved by insulating the reactor body. Chips (3–5 cm) can be sun dried to a moisture content of approximately 15% in commercial quantities, and although a lower moisture content and smaller chip size would be preferable, in practice this is unlikely to be economically viable. High inlet air temperatures are beneficial to gasifier performance but heating the inlet air is probably not economical when compared with the small gain in conversion efficiency. A smaller throat angle increases the conversion efficiency but at

Table 7
Comparison of efficiencies with gasification zone length

Parameter	Chip size (cm)			Moisture content (% d.b.)			Heat loss (%)			Throat angle (deg)		
	1	3	5	0	15	30	5	10	15	30	60	90
Efficiency at 22 cm	57.2	56.0	54.7	57.8	56.0	54.2	73.8	62.8	51.5	56.6	56.0	55.1
Optimum length (cm)	24	32	33	31	32	35	29	28	25	28	24	19
Efficiency at optimum length	57.3	56.3	55.2	58.1	56.3	54.5	74.2	63.2	51.7	57.4	56.2	55.1

the same time the gasification zone length must be increased to achieve the same conversion efficiency.

From the above study it can be concluded that the length of the gasification zone is a vital design parameter for downdraft gasifiers. A longer length enables the gasifier to operate at its maximum efficiency but it also increases the fabrication cost. A shorter length is not desirable as the gasifier may perform below its design capacity due to insufficient length for char conversion. The optimum gasification zone length has to be selected for maximum output for a given range of operating parameters. Assuming that 3–5 cm rubber wood chips with moisture content of approximately 15% (d.b.) will be used, then the gasification zone length needs to be increases from the current 22 cm to approximately 33 cm. This increase will also mean that increased insulation levels can be introduced to achieve the significant gains in efficiency that this modification will produce.

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